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OKLAHOMA CENTER FOR SCIENCE AND ARTS INTERMEDIATE PHOTOVOLTAIC SYSTEM APPLICATION EXPERIMENT

Phase II—Final Report

January 1984

Work Performed Under Contract No. AC04-79ET20630

Science Applications, Inc.
McLean, Virginia

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ABSTRACT

This report presents the key results of the Phase II efforts for the Intermediate PV System Applications Experiment at the Oklahoma Center for Science and Arts (OCSA). This phase of the project involved fabrication, installation and integration of a nominal 140 kW flat panel PV system made up of large, square polycrystalline-silicon solar cell modules, each nominally 61 cm x 122 cm in size. The output of the PV modules, supplied by Solarex Corporation, was augmented, 1.35 to 1 at peak, by a row of glass reflectors, appropriately tilted northward. The PV system interfaces with the Oklahoma Gas and Electric Utility at the OCSA main switchgear. Any excess power generated by the system is fed into the utility under a one to one buyback arrangement.

Except for a shortfall in the system output, presently suspected to be due to the poor performance of the modules, no serious problems were encountered. Certain value engineering changes implemented during construction and early operational failure events associated with the power conditioning system are also described. The system is currently undergoing extended testing and evaluation.

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SECTION 1
INTRODUCTION AND SUMMARY

This Phase II final report describes the essential features and experiences associated with the design, construction and installation of an intermediate photovoltaic application experiment at the Oklahoma Center for Science and Arts (OCSA) in Oklahoma City, Oklahoma. Certain problems encountered during the implementation phase are discussed together with the appropriate solutions utilized.

The baseline design utilizes a field of Solarex polycrystalline silicon (poly-si) solar cell module arrays, rated at 106 kW_p (NOCT 45^oC), and reflector augmentation of 1.35 to 1 at peak to enhance system output to a nominal 140 kW_p. The system consists of 1512, 65 cm by 128.5 cm (25.6 in by 50.6 in.) modules arranged in 18 series strings of 84 modules each. The 18 strings are divided into two subarrays. The modules and reflectors, separated by 11 inches at the base and supported by a standard structural steel framework, are fastened to the OCSA roof. The modules are tilted 30 degrees to the south while the reflectors are tilted 39 degrees to the North. The power from the array feeds a Windworks synchronous inverter which interfaces with the local utility at the OCSA main switchgear through an isolation/step-up transformer providing 480 volts AC service in parallel with the utility service.

The PV module, designed by SAI, provides one hundred percent cell interconnect parallelism. Each module has 6 parallel strings, each of 12 cells in series. The modules are installed with the series rows running east-west. Thus any reflector augmentation of the module, either partial or full, can be expected to result in uniform illumination of a given series string along its length, although, depending on the position of the sun, augmention of one series string could differ from that of the others. During the Phase I design study, a detailed analysis of the effects of non-uniform illumination was conducted to arrive at both the cell interconnection scheme and module-reflector arrangement to minimize the effects of single cell failures and maximize the contribution of the reflectors on an annual basis. The results of this analysis were reported in the Phase I final report.*

Integral pigtails with polarized mating connectors are incorporated in each module. This, plus the high power output per source circuit, greatly simplifies installation and subsequent maintenance. Only four junction boxes on the roof are required to interconnect the 140 kW_p array to the main DC bus.

The modules incorporate several other unique features:

- Large, 10 cm x 10 cm (4" x 4"), square polycrystalline silicon (poly-si) cells were used. The poly-si cells were sliced from silicon cast with a square cross-section mold rather than from a cylindrical, single crystal normally grown. The process offers a significant potential for cost reduction.
- A simple circuit incorporating a light-emitting diode (LED) was included in each module. The LED indicates proper forward-bias condition, thereby simplifying fault isolation without extensive instrumentation. LED out indicates module is not producing power (e.g., reverse bias).

Table 1-1 contains all key system characteristics for easy reference. Figures 1-1 through 1-3 are pictures of the completed system.

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* "A Solar Photovoltaic Flat Panel Applications Experiment. At the Oklahoma Center for Science and Arts", Final Report for Phase I, Submitted by Science Applications, Inc., for work performed under contract number DE-AC04-78ET 23063.

Table 1-1. System Characteristics

PHOTOVOLTAIC CELL

Material:	Polycrystalline Silicon
Size:	10 cm x 10 cm (4" x 4") - nominal
Voltage:	0.44V
Power:	1 watt

MODULE

Cover plate:	5 mm (3/16") tempered glass
Size:	65 cm x 128.5 cm (25.6" x 50.6") overall
Number of cells:	72
Electrical configuration:	12 series x 6 parallel rows with 100 percent parallel interconnections
Voltage:	5V (1,000 w/m^2, 25 degrees centigrade)
Current:	14A (1,000 w/m^2, 25 degrees centigrade)
Power:	70 watts

SOURCE CIRCUITS (series string of modules)

Number of modules:	84
Voltage:	420V
Current:	14A
Power:	5,880 watts (without reflector augmentation) 7,760 watts (with full reflector augmentation)

ARRAY

108,864 cells; 1512 modules; 18 strings; two subarrays in parallel (126A @ 420V)

Total Voltage:	420V
Total Current:	252A
Total Power:	105,840 watts (without reflector augmentation) 139,708 watts (with full reflector augmentation)

PEAK POWER OUTPUT

140 kW with full reflector augmentation

REFLECTORS

One layer of 3 mm (1/8") silverplated float glass laminated to second layer of 3 mm (1/8") clear glass

Size:	48.3 cm x 128.5 cm (19" x 50.6")
Total area:	957.6 m^2 (10,308 ft^2)
Augmentation:	35 percent at peak

Table 1-1. System Characteristics (continued)

POWER CONDITIONING UNIT

Six pole line synchronous Gemini inverter with peak power tracking
and a 1:1.33 step-up transformer.
Input: 320 to 450 V DC
Output: 480 V AC 3 phase 60 hz
Operation: fully automatic

EXPERIMENTAL DATA ACQUISITION SYSTEM

80 sensors to measure voltages, currents, instantaneous and cumulative
power, module temperature, insolation and other meteorological data.
A minicomputer scans sensors and records data on magnetic tape - hourly printout of selected data, periodic summaries in graphic form.

LOCATION

Latitude:	35^{o} 31' 57" (35.5325 degrees N)
Longitude:	97^{o} 28' 56" (97.4822 degrees W)
Elevation:	334 m (1097 ft) - street level
	348 m (1141 ft) - top of roof

MODULE TILT

30^{o} to the south from horizontal

REFLECTOR TILT

39^{o} to the north from horizontal

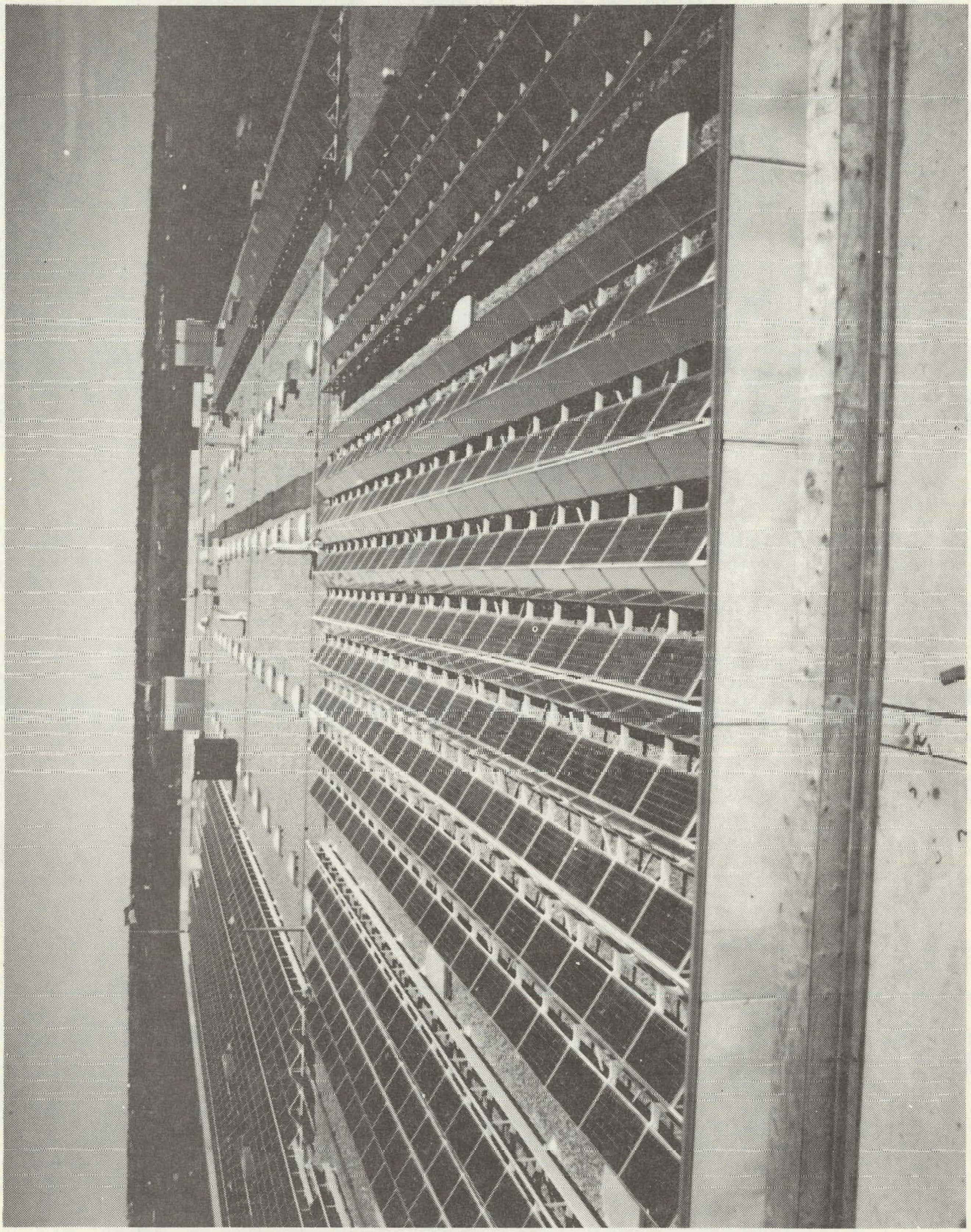


Figure 1-1. Roof Top View Looking East of the 140 kW_p Installation at Oklahoma Center for Science and Arts

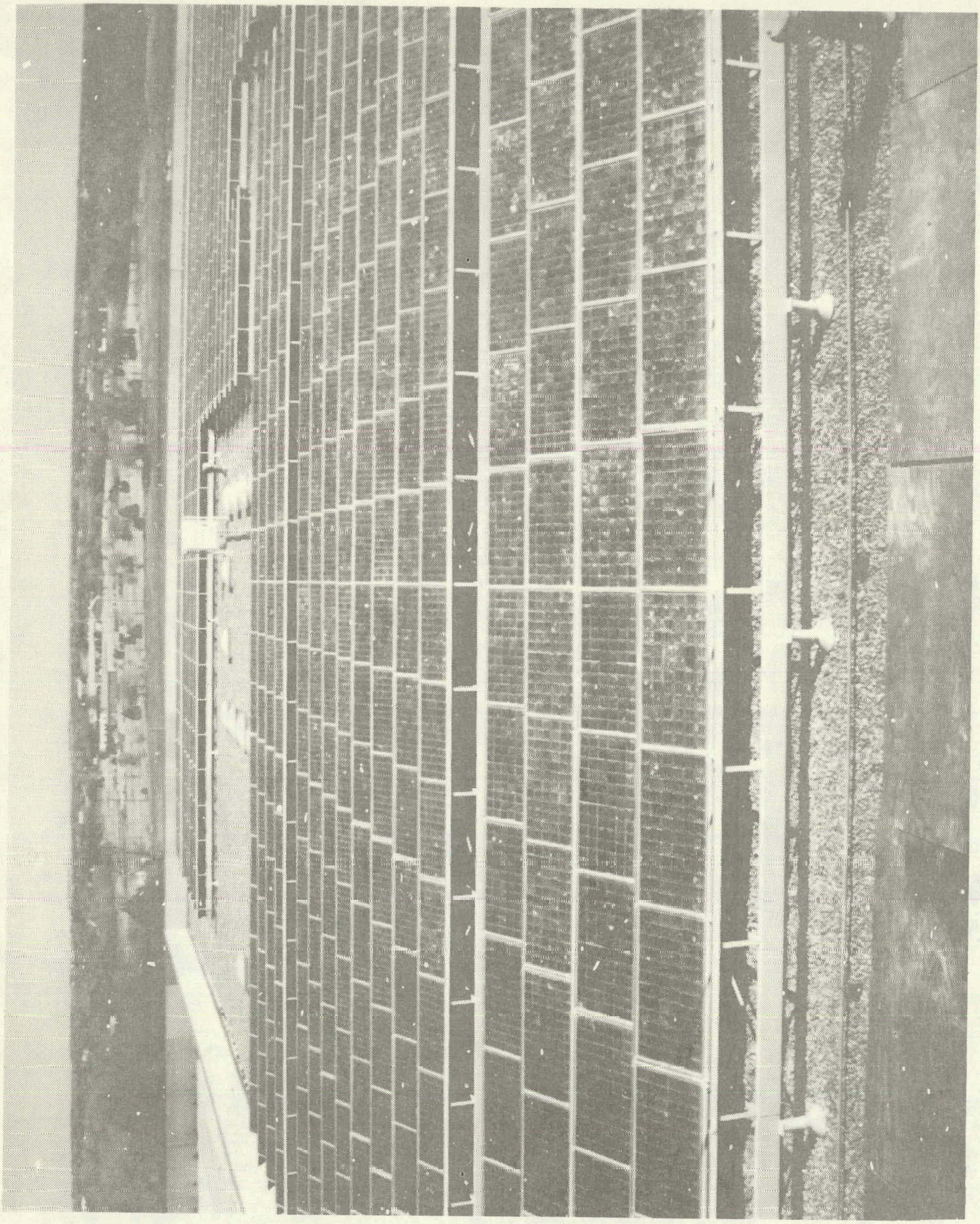


Figure 1-2. Roof Top View Looking North of the 140 kW_p System at Oklahoma Center for Science and Arts

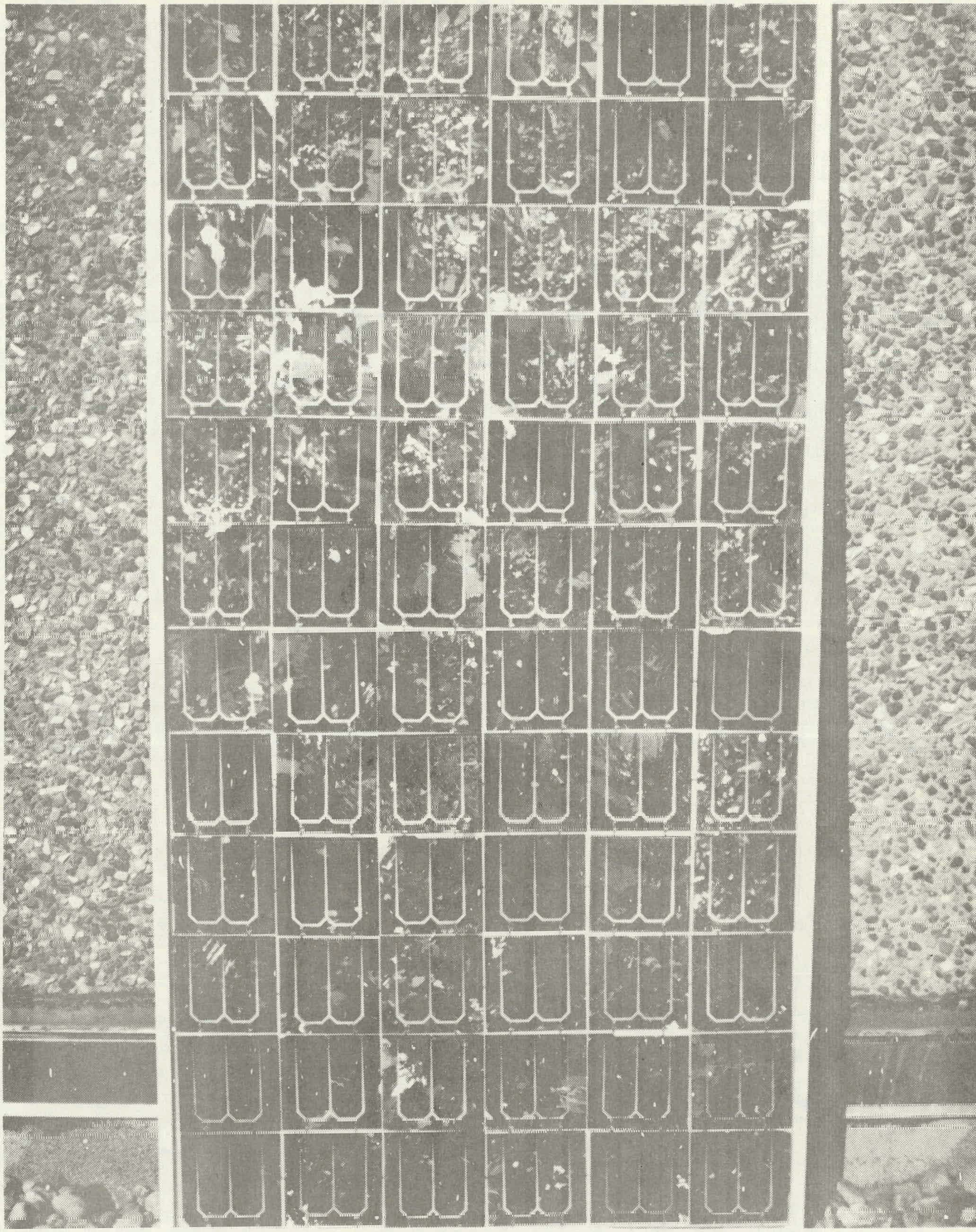


Figure 1-3. Close-up of Solarex Polycrystalline Silicon 2 Feet by 4 Feet Module

SECTION 2
SUMMARY OF THE PHASE I DESIGN

2.1 BACKGROUND

The specifications and design of the OCSA photovoltaic power system were developed in detail in Phase I during the period October 1978 through Feburary 1979. The OCSA site (also referred to as the Kirkpatrick Center) was selected from a group of six candidate sites for the following reasons:

- The facility loads were representative of a large number of commercial and institutional facilities representing a potentially large market for photovol-taics
- The insolation and other climatic factors are typical of a large portion of the U.S.
- The facility structure was ideally suited for the application: the essentially flat roof was large enough to accommodate an array that could supply the projected peak loads, its orientation was E-W, and the roof needed no reinforcement to accommodate the added loads
- The surrounding terrain was either parkland, zoo, or under control of OCSA, making it virtually immune from construction of any structures or other encroachments that would shade the array.
- The OCSA board of trustees were enthusiastic supporters of the project and were willing to provide a significant cost sharing.
- The facility attracts hundreds of thousands of visitors each year, giving a PV system high public visibility

The principal design tool was the SOLCEL computer program. The program was modified to accommodate the use of reflectors, non-uniform illumination of the vertical extent of the module and the end effects introduced by the finite E-W length of the reflectors. It was also modified to permit an accurate representation of polycrystalline silicon cell performance.

The major design variables included module tilt angle, reflector tilt angle, module row spacing, reflector row extension length (to reduce non-uniform end effects), series-parallel connections within the modules, source circuit voltage, energy storage alternatives, and buy-back rate structure offered by the area utility, Oklahoma Gas & Electric Co. (OG&E). Evaluation criteria were primarily based upon the correspondence between system output and facility load profile, and the bus-bar energy cost based upon 1982 cost goals.

Under Phase I, two system size options were designed, one a 350 kWp system and an alternative 150 kWp design. Due to the funding limitations, the Department of Energy selected the 150 kWp design. During Phase II, the system output was reduced to a nominal 135 kW peak to conserve funds.

Table 2-1 summarizes the major system, subsystem and component alternatives, evaluated and selected.

2.2 SYSTEM OBJECTIVES

The system objectives were derived from the PRDA 38 guidelines, an assessment of PV and related technology, the physical characteristics of the site and the load demand profile for the facility.

Furthermore, SAI had proposed to utilize the emerging polycrystalline silicon photovoltaic cell technology for several reasons. Polycrystalline cells and modules had hitherto been produced on a limited laboratory scale. The production experience attainable in manufacturing a large quantity promised substantial cost reductions for future projects.

Simplicity, high reliability and economy in installation and operation were adopted as system objectives. These objectives led to the design of a low voltage, high current module; the incorporation of factory-installed module interconnection wires with mating connectors; a bias indicating circuit in the modules; and reflector augmentation of the PV modules.

Table 2-1. System, Subsystem, and Component Alternatives

ISSUE	RANGE OF ALTERNATIVES CONSIDERED	SIGNIFICANT PROBLEMS OR ADVANTAGES	PREFERRED ALTERNATIVE
Module Series/Parallel Interconnections	• 72 Cells in Series	• Reduces benfit of reflector, hot spots likely, high losses, high cost of module interconnects	• 6 Strings of 12 cells with cell-by-cell parallelism
	• 6 Strings of 12 cells each	• Retains benefit of reflector but does not minimize losses	
	• 6 Strings of 12 cells with cell-by-cell parallelism	• Retains benefit of reflector and minimizes losses	
Methods to Mitigate Transients	• Parallelism	• Retains benefit of reflector and reduces the effects of failures and non-uniform illumination	• Maximum intramodule parallelism
	• Bypass diodes	• Will reduce the effects of reverse bias, and cell and module failure	• Bypass diode integral to module
	• Blocking diodes	• Will prevent forced reverse current in entire string	• Blocking diode at end of string
	• Extended reflector	• Will mitigate hot spot generation due to end effects	• Reflector extended 1 foot
Array Size/Orientation	• Module angle 10 to 55 degrees	• Angles chosen based on the lowest busbar energy cost	• Module angle 30 degrees S
	• Reflector angle 21 to 39 degrees		• Reflector angle 39 degrees N
	• Shading angle 21 to 31 degrees		• Shading angle 25 degrees
	• Shading angle 21 to 31 degrees		• Array size--1512 modules
Power Conditioning Alternatives	• Manufacturers:		
	-- Windworks	• Windworks is the least expensive	• Windworks
	-- Westinghouse	• Westinghouse is best performer at more than five times the price	
	-- Garrett	• Garrett is a standard UPS system (lower performance, higher price)	
	• Range limit of input voltage ± 0 to 20 percent	• Maximum power point voltage varies with temperature and insolation	• Input voltage range ± 20 percent
Array Circuit Design	• String length 64 to 120 modules	• Length dictated by open circuit system voltage of less than 600 V.	• 84 modules/String
Electrical Energy Storage	• No storage to 1000 kWh storage	• Battery storage is not cost-effective	• No storage
Cooling Alternatives	• One-side/two-side natural convection	• One-side reduces output due to higher temperature	• Two-side natural convection
	• Fins	• Expensive and difficult to integrate into design	
	• Fans	• Expensive and energy intensive	
	• Fins and Fans	• Expensive, difficult to integrate into design and energy intensive	
System concepts	• Match projected (1981) summer peak load	• Matches load expected when system is commissioned	• Matches load in winter
	• Match present summer peak load	• matches current load	
	• Match present winter peak load	• Will only match load in winter but will be a smaller system	

A system output that matched the facility load profile as closely as possible was also adopted as a system objective. The reflector tilt angle, combined with the module tilt angle, provided an additional degree of freedom in shaping the output profile.

2.3 SITE DESCRIPTION

The main structure is the Kirkpatrick Center, a precast concrete structure approximatley 61 m x 126.8 m (200 ft x 416 ft), with the long dimension running exactly E-W. The vertical distance from the main floor to the roof surface is 10.7 m (35 ft), and the essentially flat roof is 1.07 m (42 inches) below the vertical walls. The roof structure is made up of precast concrete "double tee" sections. The building is adjacent to the Lincoln Park Zoo, in the northeastern part of Oklahoma City. There are no vertical obstructions near the building and the land to the south and the east is either part of the zoo or public park.

The roof was designed to support substantial loads and required no structural modifications to accommodate the PV system. One hundred twenty-eight double-dome skylights, each nominally .61 m (2 ft) high, on the roof imposed a requirement for a low profile array, carefully located to minimize shading of the skylights.

The activities within the building include hands-on dynamic exhibits that demonstrate physical laws and scientific principles, a planetarium, art exhibits, an air and space museum, and facilities for meetings of scientific and cultural groups. While the scope of the activities is dynamic, the electrical load profile is dominated by requirements for heating, air conditioning and lighting, and is predictable. The facility is open throughout the year from 10 AM to 5 PM Monday through Saturday, and 12 PM to 5 PM on Sundays.

2.4 DESIGN OVERVIEW

A simplified block diagram of the PV system is shown in Figure 2-1. Both the larger 350 kW_p and the smaller 135 kW_p systems, the latter constructed during Phase II, are similar in schematics and all essential design features, except that the smaller version has a substantially reduced capacity for power feedback to the interfacing utility system.

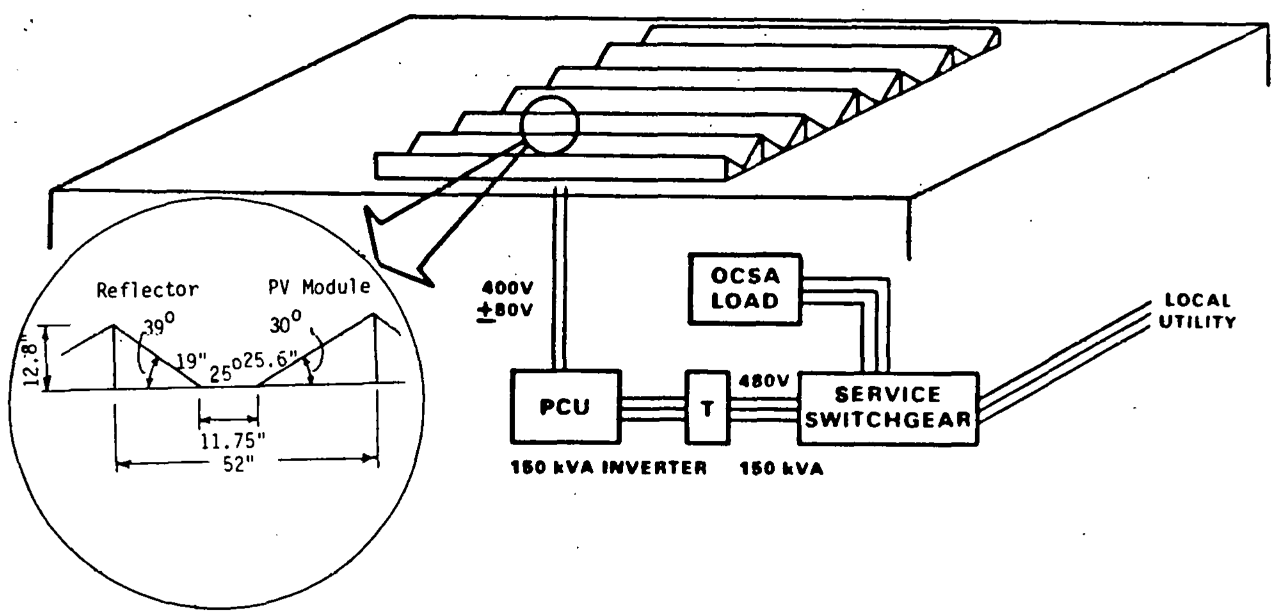


Figure 2-1. Simplified System Concept and Block Diagram

The installed system consists of 1512, 65 cm (25.6 inches) by 128.5 cm (50.6 inches) poly-Si Solar cell modules with the total PV field rated at a design value of 106 kW_p at 25°C. A reflector augmentation of 1.35 to 1 peak enhances system output to a nominal 140 kW_p. The modules and reflectors, tilted respectively 30 degrees to the south and 39 degrees to the north, are separated by about 30 cm (11.75 inches) at the base to provide easy access between the rows of PV modules and reflectors. A Windworks Synchronous inverter-based power conditioning system (PCS) provides AC power of the desired quality (phase, frequency, harmonic distortion) as well as allows interface with the local utility at the OCSA main switchgear.

The structure supporting PV modules and reflector mirrors was fabricated from standard shapes of carbon steel. The structure was largely prefabricated in the shop. The basic structural module supported eight PV modules and eight reflector panels. Some six and four unit modules were required to adapt the row lengths to obstructions on the roof. The structural modules are attached to the roof structure by telescopic foundations to account for the variations in the pitch of the roof. This provided a PV array field with all strings having equal elevations at the top, a feature deemed essential to obtain maximum advantage from the reflector miror augmentation and to minimize non-uniform illumination effects.

The system, as installed, is designed to provide approximately 200 MWh in annual electrical output (about 20 percent of the 1981-82 projected load), or roughly 120 barrels of oil equivalent.

Phase I activities involving systems analysis, design, and component development and testing resulted in a unique system design for the OCSA and other related applications. The unique results of Phase I included:

- The development and testing of large polycrystalline silicon solar cell modules with 10 cm x 10 cm (4 in. x 4 in.) square cells.

- A module design not only with high packing density, but also with high efficiency, low voltage-high current operation, ready fault identification, and simplicty of installation.

- A module with high reliabiliity because of maximum parallelism of intercell connections.

- A module proven for its ruggedness to severe environmental conditions typical of the large part of the United States.

- A system with a low profile and equipped with easy access for operation and maintenance, adequate sensors for data collection, and an independent public display.

- A combination of module and reflector tilt angles to produce an annual power output profile similar to the facility demand profile, while minimizing the cost of power production.

- The potential for cost reduction through poly-Si solar cell technology development, the economic ramifications of which have become increasingly established.

- The experience derived from utility feedback arrangements to help establish a standard for similar arrangements throughout the country.

The system fabrication, installation and operation during Phase II of the project provided a considerable learning and experience data base including the identification of specific problem areas that can be avoided in the development and implementation of similar systems and components in the future. The sections that follow describe major key elements of the system, its performance characteristics, problems that were encountered during the implementation of the Phase II program and the appropriate solutions applied to achieve an operating system to provide long-term experience in the operation, maintenance and evaluation of all hardware.

SECTION 3
MAJOR SYSTEM ELEMENTS

3.1 PHOTOVOLTAIC MODULES

Key design features of the modules, summarized below, were dictated by the system objectives:

- Large square, 10 cm x 10 cm (4" x 4"), photovoltaic cells were used to achieve high packing density and thereby reduce structure costs.
- Polycrystalline cells were used to exploit the emerging technology and to foster future reduced costs.
- 100 percent parallel cell interconnections were used to compensate for the non-uniform illumination from reflectors during spring and fall.
- The modules were configured for low voltage-high current to minimize the number of source circuits and the field cabling.
- Integral pig-tails with mating connectors were provided to reduce field wiring costs.
- An LED, an indicator of the bias status of the module, was incorporated to facilitate easy, fast trouble-shooting.

The principal module parts are shown in Table 3-1. The module construction is presented in Figure 3-1. The module superstrate is 5 mm (3/16") high-strength, water-white tempered glass. The relatively heavy glass was required because of the hail environment.

A typical module I-V curve is shown in Figure 3-2. The fill factor for the poly-si modules is much lower than that for modules made up from single crystal silicon cells. As a result of the soft I-V curve for poly-si modules the system performance is relatively insensitive to small deviations from the peak power voltage. More detail on the electrical characteristics of the modules is contained in Section 5.

Table 3-1. Polycrystalline Silicon Solar Cell Module
Glass - 0.5 cm (3/16") Tempered Sunadex -- 65 cm x 128 cm (25 9/16" x 50 3/8")
Encapsulant - Clear - Dow-Corning Sylgard 184
Primer - Glass to Clear Encapsulant -- RTV 108
Interconnects - Tinned Copper 110 - .01 cm x 0.178 cm (.004" x .070")
Primer Cell to Encapsulant - Dow-Corning 1200
Bus Bars - 0.5 mm x 5 mm -- Cut to Length
Fiber Board - 0.16 cm x 1.5 cm x 59 cm (1/16" Thick x 3/5" x 23")
Encapsulant - White - Dow-Corning Sylgard 184 with 3% TiO_2
Gasket - White Silicone Molded to Fit Glass
J Box - Aluminum, 10 cm x 10 cm (4" x 4")
Diode - 50V 20A RCA SK3607

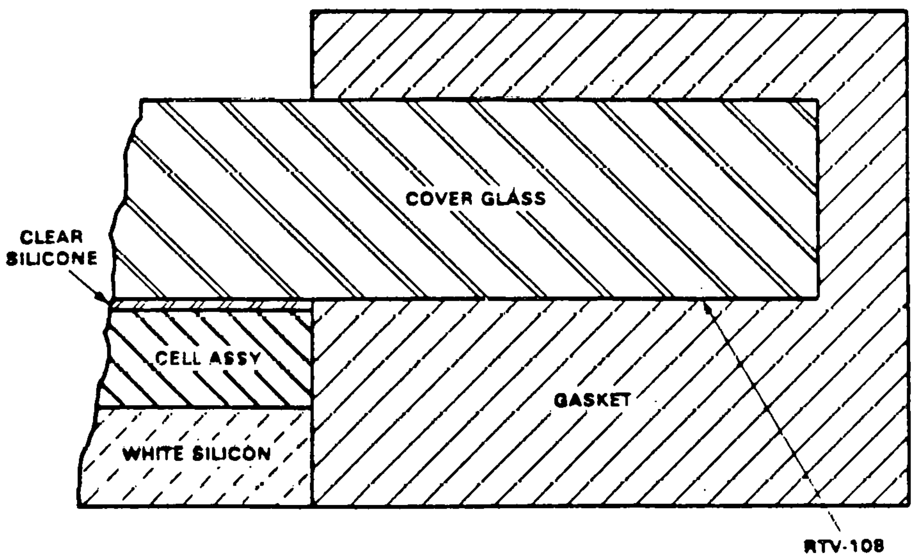


Figure 3-1. Solarex Module Assembly

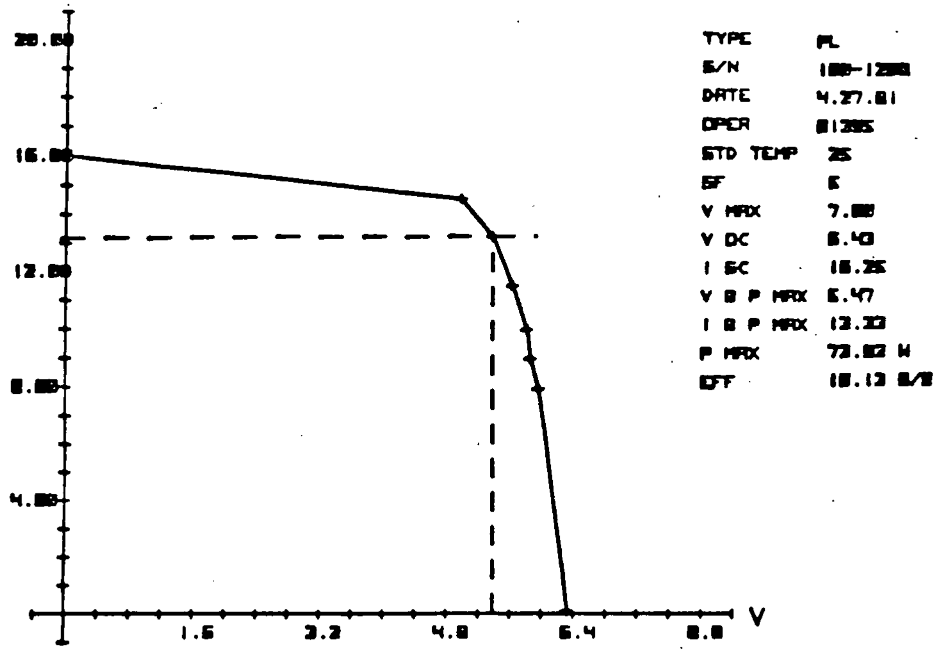


Figure 3-2. Typical Module I-V Curve as Received from Manufacturer

3.2 REFLECTORS

An extensive tradeoff analysis of reflector material and construction showed silvered glass reflectors to have the best lifetime cost benefit ratio despite their relatively high first cost.

The reflectors selected were made up of two layers of 3 mm (1/8") float glass. The inner surface of the top layer is silvered, and the silver is protected by a plated layer of copper and a coating of organic material. The two glass layers are bonded together with vinyl. The construction is much like automotive safety glass. The reflectivity of the mirror is greater than 85 percent when clean. Performance estimates were based upon a reflectivity of 75 percent to account for surface fouling.

Reflector Augmentation Effects

The contribution of the reflectors is difficult to predict by any closed form method. Figure 3-3 shows the local apparent noon effects of the reflectors with regard to direct insolation. Curve A shows the percentage of direct normal insolation incident on the modules without considering the effects of the reflectors. Curve B shows the percentage of Curve A that would be reflected onto the modules if the reflector surfaces were perfect. Curves C and D show the percentage of direct normal insolation incident on the module surfaces assuming reflectivities of 0.75 and 0.85, respectively.

The non-isotropic nature of diffuse insolation makes any assumptions regarding reflector augmentation of diffuse light suspect. To first order, the mirrors replace the backs of the next row south with an image of the sky, and the modules "see" the same portion of the sky which they would if there were no row to the south. The modules to the South block 14 percent of the sky. Thus, the diffuse enhancement would be about 14 percent for perfect reflectors, and 12 percent and 11 percent, respectively, for mirrors with reflectivities of 0.85 and 0.75.

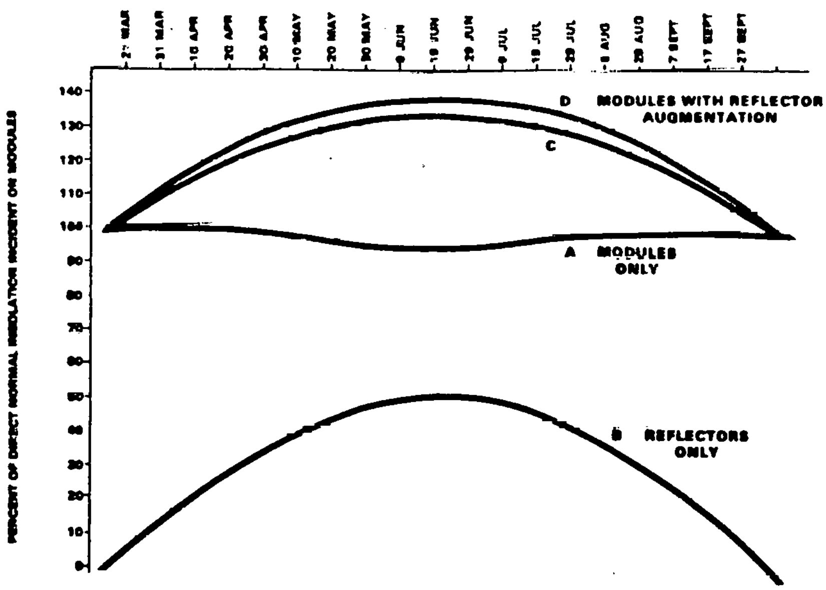


Figure 3-3a. Reflector Effects for Direct Normal Insolation at Local Apparent Noon

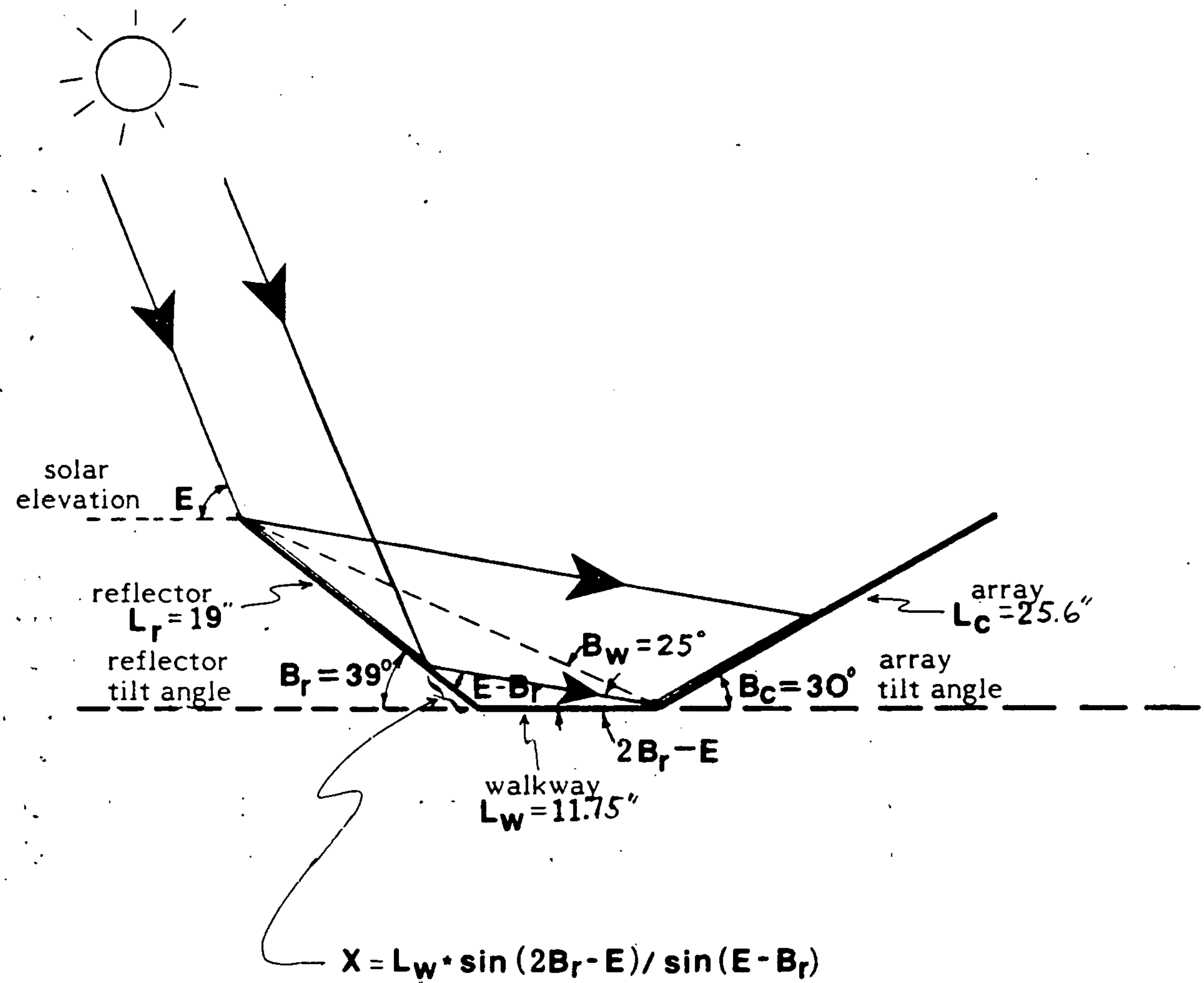


Figure 3-3b. Geometry for Calculating Reflector Enhancement

Figure 3-3c. Calculation of Reflector Enhancement Versus Time of Year

Dates	Solar Declination	Solar Elevation at Noon*	Enhancement Percent at 80% Reflectance**
Dec 22	-23.45°	31.2°	0%
Jan 21, Nov 22	-20	34.6	0
Feb 9, Nov 3	-15	39.6	0
Feb 23, Oct 20	-10	44.6	0
Mar 8, Oct 6	- 5	49.6	0
Mar 21, Sep 23	0	54.6	2.7
Apr 3, Sep 10	5	59.6	10.9
Apr 16, Aug 28	10	64.6	19.1
May 1, Aug 12	15	69.6	27.4
May 21, Jul 24	20	74.6	36.0
Jun 22	23.45	78.1	42.6

* Solar elevation above the horizontal at noon can be calculated as follows:

L	=	latitude = 35.4° in Oklahoma City
D	=	solar declination angle depending on time of year
E	=	solar elevation at noon = 90° + D - L.

** The enhancement percent is the theoretical amount of direct beam radiation reflected from the mirror onto the array, expressed as a percent of direct beam radiation incident on the array when no reflector is present. The enhancement percent at noon can be calculated as follows:

R	=	reflector percent reflectivity = 80%
B_c	=	collector tilt angle = 30°
B_r	=	reflector tilt angle = 39°
B_w	=	walkway-related tilt angle = 25°
L_r/L_c	=	reflector to collector length ratio
	=	$\sin B_c/\sin B_r$ = .79
L_w/L_r	=	walkway to reflector length ratio
	=	$\sin B_r/\tan B_s - \cos B_r$ - .57
E	=	solar elevation angle = 90° + D - L
EP	=	enhancement percent
	=	$R/\sin(E+B_c) * (L_r/L_c) * [\sin(E-B_r) - (L_w/L_c) * \sin(2B_r - E)]$
		for $2B_r - B_s \leq E \leq 2B_r$,
	=	0 for $E \leq 2B_r - B_s$.

3.3 SUPPORTING STRUCTURES

The low profile of the module array field layout allowed the use of a simple, lightweight support structure. The system uses standard steel shapes which were efficiently prefabricated. The structure was built of subassemblies, with each unit designed to hold eight modules and eight reflector mirrors. The basic dimension of each subassembly is 5.17 m (16 ft 11.5 inches) in the E-W direction and 2.64 m (8 ft and 7.75 inches) in the N-S direction. Figure 3-4 shows a view, looking west, of a typical N-S cross section. The heights of the supporting columns vary to suit the drainage slopes on the roof (see paragraph 4.1 for further detail). The primary E-W members are 7 lb channels, 24.9 cm (9.8 inches) in depth. A number of four-module and six-module subassemblies were also used to provide the required row lengths.

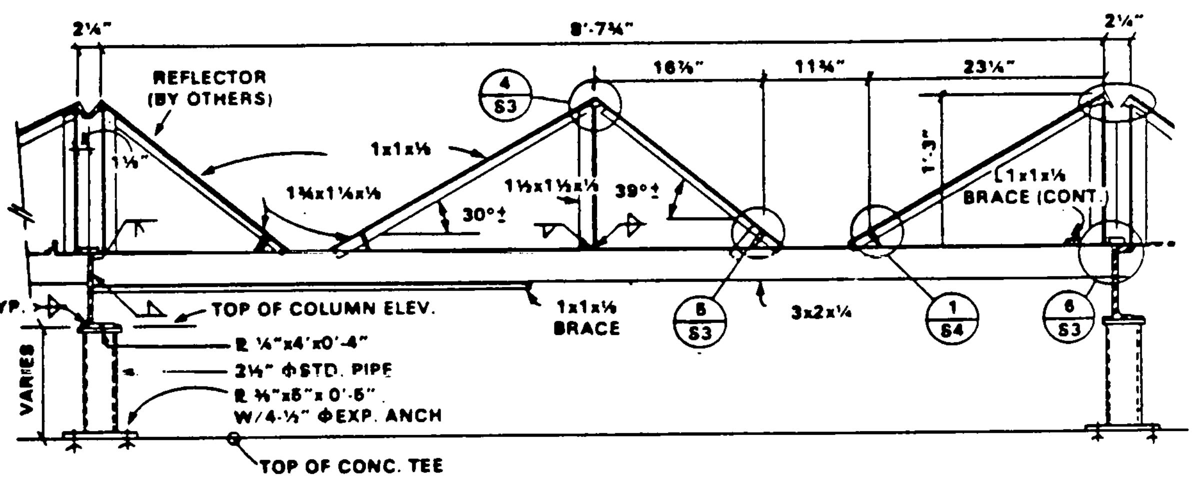


Figure 3-4. Typical N-S Cross Section, Looking West, of the Supporting Columns

The Solarex modules have no metal frames. Therefore, each edge was enclosed in a vinyl glazing gasket, and the module held in place with hold-down strips which compress the gaskets, as shown in Figure 3-5.

3.4 ARRAY WIRING

The module-to-module interconnection was accomplished by simply interconnecting the module pig-tails. The connectors used were "CAMLOCK" J-Series (Empire Electric Co.). They were oversized for the application (a 600 Ampere connector for an 18 Ampere requirement). However, no other connector having the required capacity that was also UL listed for outdoor use could be located.

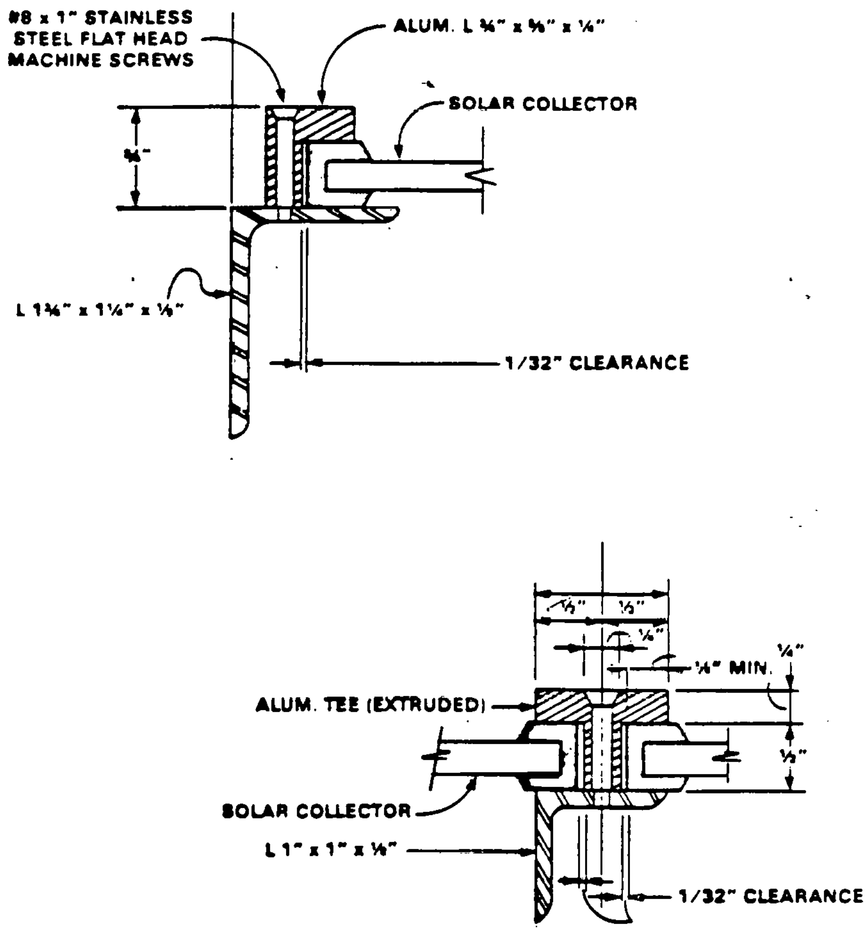


Figure 3-5. Support Structure Module Hold-Down Strip's. Typical End and Interior

Each of the four large string power collection (SPC) boxes located on the roof, is equipped to terminate and parallel five source circuits. A blocking diode mounted in a heat sink was provided for the positive end of each source circuit, as shown in Figures 3-6 and 3-7. AWG# 8 conductors were run in conduit from the end of each source circuit to one of the SPC boxes. A pair of AWG# 4 conductors was run from each of the four SPC boxes to the electrical equipment room.

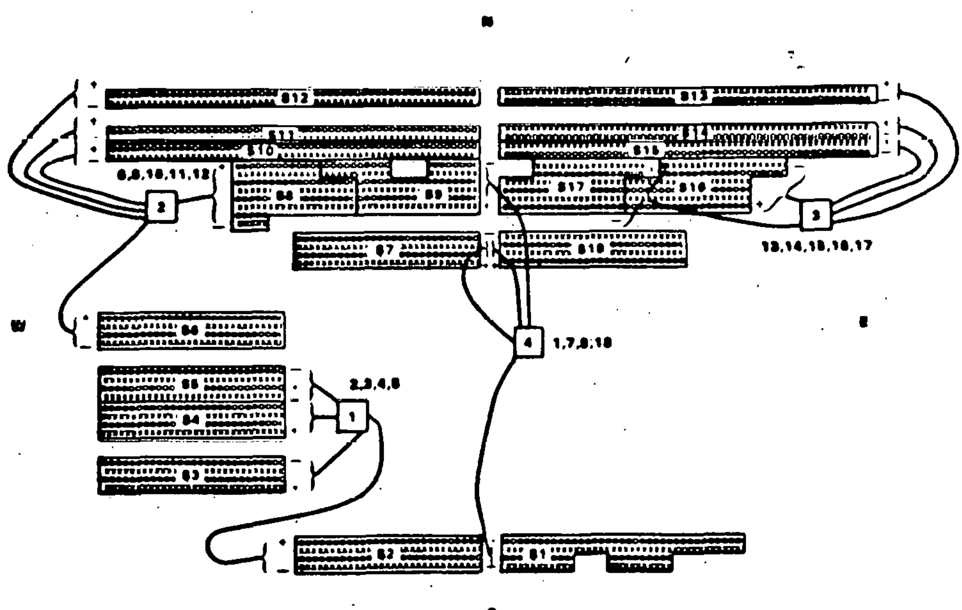
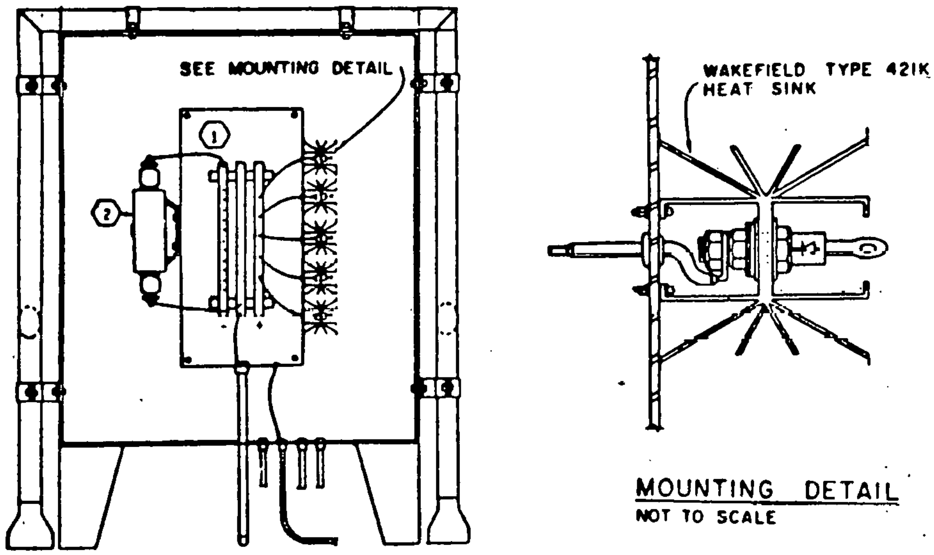


Figure 3-6. PV Array Field Layout Illustrating String/ SPC Box Location



1. Panel box with panel board, main bus bars, copper, sized for single phase, three wire, 480 volt, 225 ampere, service to 12 single pole, bolt on circuit breakers. All panels are bottom fed. Ground is connected to the center bus.

2. Lightning arrestor.

Figure 3-7. String Power Collection Box Detail

A simplified schematic of the system is shown in Figure 3-8. The DC switches are four-pole 225 molded case switches with shunt trips. Two poles are series connected on each path to provide sufficient total gap to interrupt up to 600 VDC. A detail of the switches is shown in Figure 3-9.

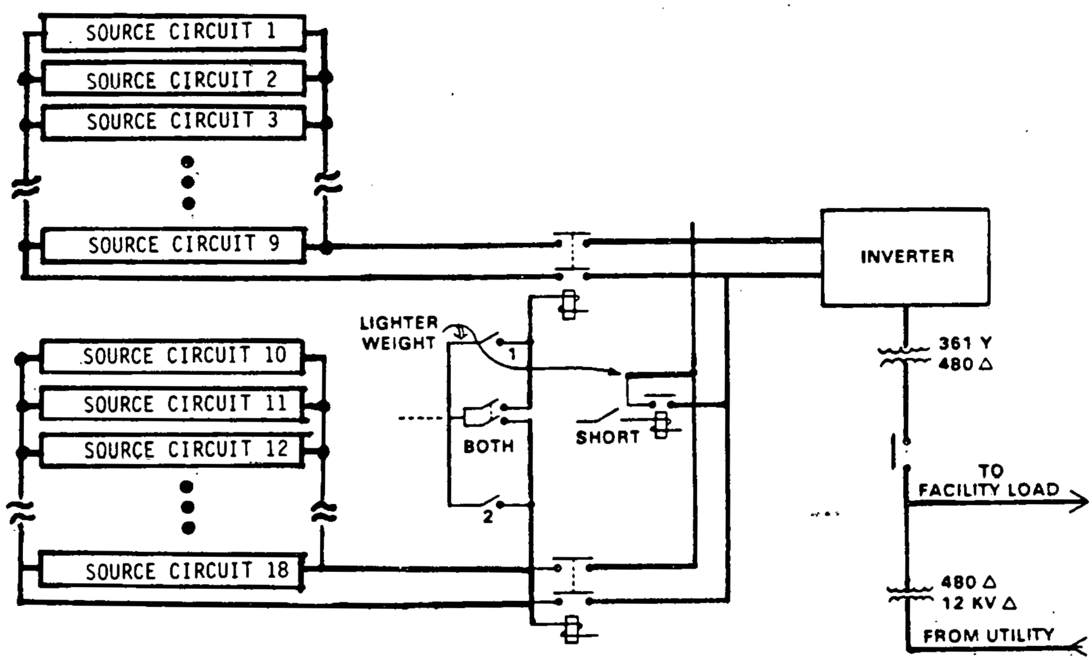


Figure 3-8. OCSA PV System Simplified Schematic

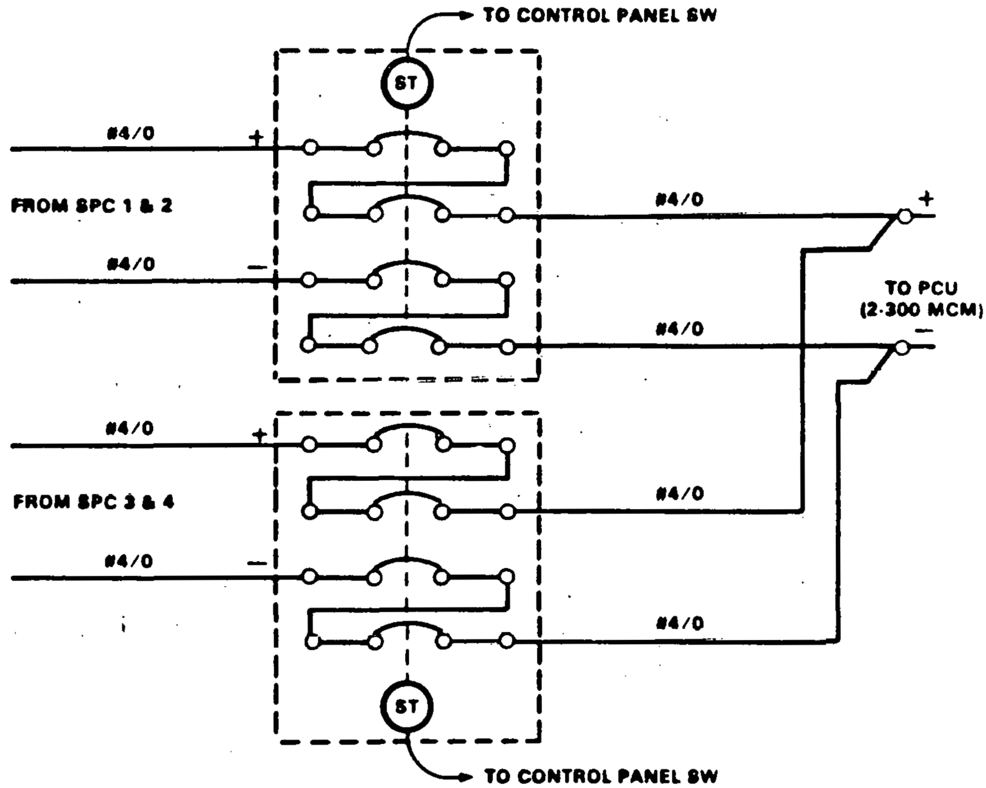


Figure 3-9. Switch Detail

In the equipment room the output from the SPC boxes were paralleled to form two sub-array circuits (nine branch circuits each). Each sub-array circuit terminates in a two-gang double pole circuit breaker with a remote operating solenoid. The two gangs are connected in parallel to provide the gap needed to interrupt the DC voltage. The outputs of the breakers are paralleled and routed to the PCS.

There is no main array breaker or switch. Instead a controller that permits simultaneous operation of the two sub-array breakers is provided. Three remote push-button switches permit operation of either or both sub-array breakers.

3.5 POWER CONDITIONING SYSTEM

The power conditioning system is a GEMINI six-pole inverter manufactured by WINDWORKS, Inc. The principal reason for its choice was to gain experience with an inexpensive unit in a large PV system. In addition to its relatively low cost, its input voltage is higher than more elaborate Power Conditioning systems (PCS's), permitting longer source circuits (series strings of modules). A result of using longer source circuits is that a fewer number of them is required, providing a proportional reduction in the number of conductor and conduit runs. No increase in conductor size over that required for a lower voltage source circuit is necessary since the current is fixed by the module characteristics. The net beneficial effect is the reduction in field wiring costs. Its principal disadvantage is the power factor which is a function of the ratio of the DC input voltage to the maximum design operating voltage. Figure 3-10 shows the power factor vs. input voltage. The efficiency as a function of the percentage of full load current is shown in Figure 3-11.

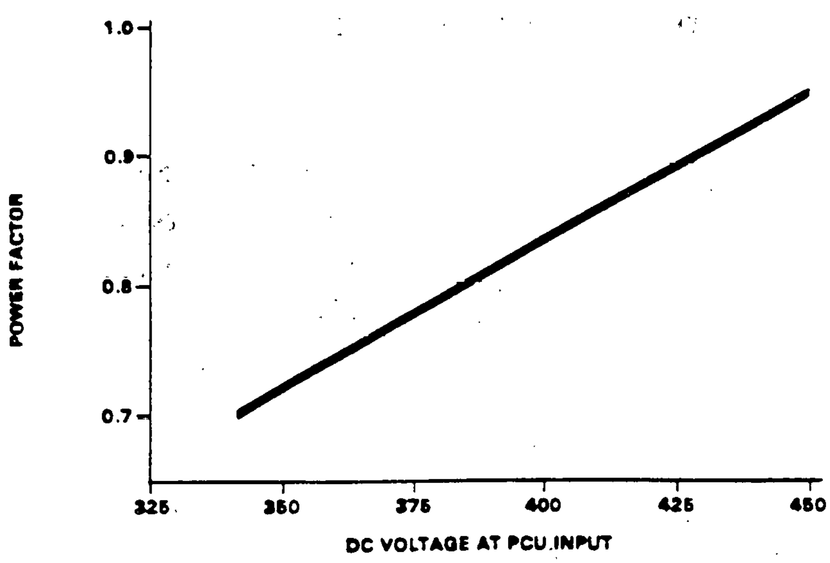


Figure 3-10. PCU Power Factor vs. Input Voltage

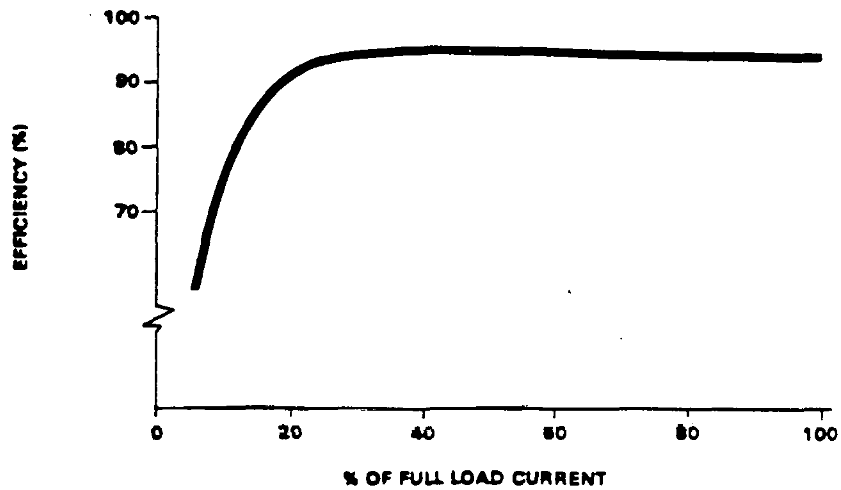


Figure 3-11. Power Conditioner Efficiency versus Percent of Full Load

It is possible that the power factor could become unacceptable under some conditions of peak power tracking. Accordingly, a constant voltage control circuit board, which can be substituted for the peak power tracking circuit board, was also procured. If necessary, the circuit can be used and the voltage selected to provide the desired power factor. During Phase III, it will be used to acquire data on the constant voltage mode of operation.

The PV array was limited to a series configuration that would not exceed 600 V under open circuit conditions. This permitted the use of cable, conduit, termination hardware, switchgear and other components approved for use under the low voltage category (600 V or less) of the National Electric Code. An open circuit voltage greater than 600 V would have required upgrading of all components to meet the requirements of the National Electric Code for high voltage systems. The resultant PCS output voltage is 361 VAC. A combination isolation and step-up transformer produces the 480 V output to the utility tie point.

3.6 SYSTEM INSTRUMENTATION

The instrumentation was designed to comply with the uniform data requirements for PRDA systems and to permit efficient operation of the OCSA system after removal of the GFE on-site data acquisition system (ODAS).

Two instrument modules are provided to interface the power components of the PV system with the ODAS and to display key parameters. Both were manufactured by Ohio Semitronics. Functional diagrams of the DC and AC modules are shown in Figure 3-12 and Figure 3-13. The AC module has

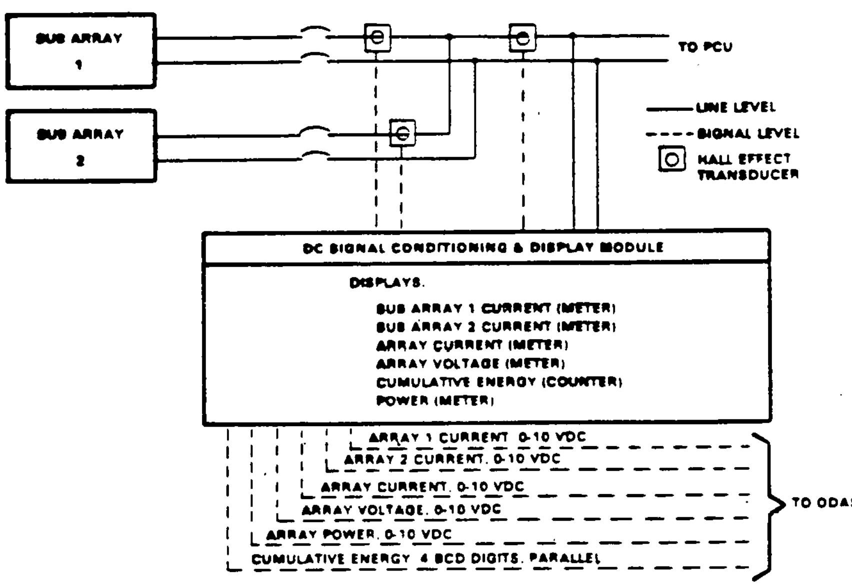


Figure 3-12. DC Instrumentation Module

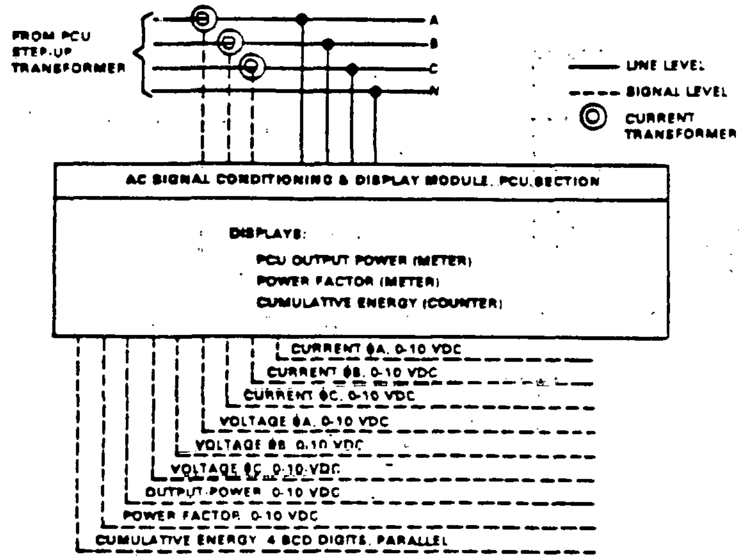


Figure 3-13. AC Instrumentation Module

two essentially identical sections, one to monitor the output of the PCS and the other to monitor the utility power to the facility. Only the instrumentation for the PCS output is shown in Figure 3-13.

The instrument modules are self-contained and are not dependent on the ODAS. All analog outputs to the ODAS are accessible through jacks on the front panel to permit monitoring of the parameters by means of a voltmeter or a chart recorder.

The meteorological instrumentation is the standard GFE configuration provided for all PRDA-38 projects. An additional pyranometer, set at the module angle of 30°, is also included.

Three PV modules are instrumented with 14 temperature sensors each. The purpose of the high density placement is to provide data on the temperature distributions during periods of non-uniform reflector augmentation. Figure 3-14(a,b) shows the placement of the temperature sensors and a diagram of the sensor circuit.

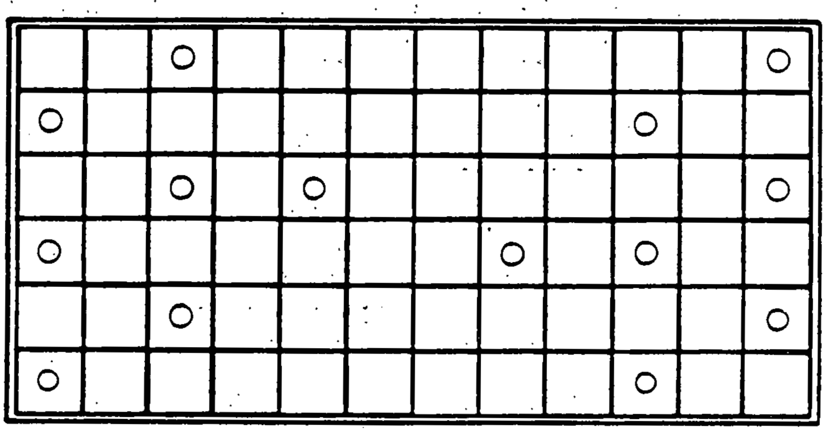


Figure 3-14a. Thermistor Locations on Back Surface of Modules (Each Square Represents One PV Cell)

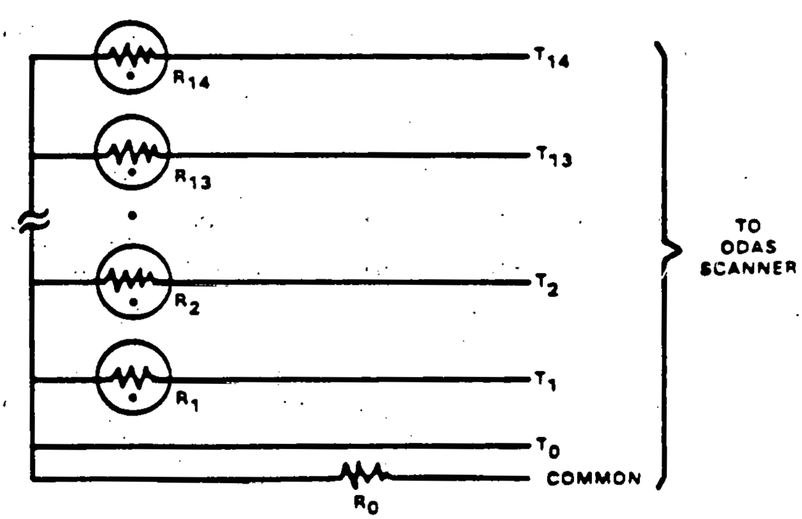


Figure 3-14b. Thermistor Monitor Circuit

Precision, matched thermistors are used to avoid the problems frequently encountered with thermocouples. In scanning the sensors for each module, the resistance through the conductors and the current-limiting resistor is first read and recorded. This value is subtracted from the readings of each sensor to yield the resistance of each thermistor.

The current limiting resistor is not required with the ODAS since the low level of the sensing current and the short monitoring interval preclude any significant self-heating of the thermistor. However, it is prudent to use one since the sensors may be monitored by other means after removal of the ODAS.

SECTION 4

DESIGN CHANGES DURING IMPLEMENTATION

The system design was completed in detail during Phase 1. Except for one change to accommodate a discrepancy in the facility "as-built" drawings, no changes would have been required to implement the design. However, several value engineering changes were made, and external factors resulted in a requirement to relocate the equipment room and to modify the PV array layout.

4.1 VALUE ENGINEERING CHANGES

4.1.1 Structural Support Foundations

The facility roof is not a true plane. Figure 4-1 illustrates the slopes along N-S profiles on typical portions of the roof. The original concept for foundation called for each support to be tailored in height to suit its position on the N-S line. This was to produce a true plane for the array. In addition to the relatively large number of sizes

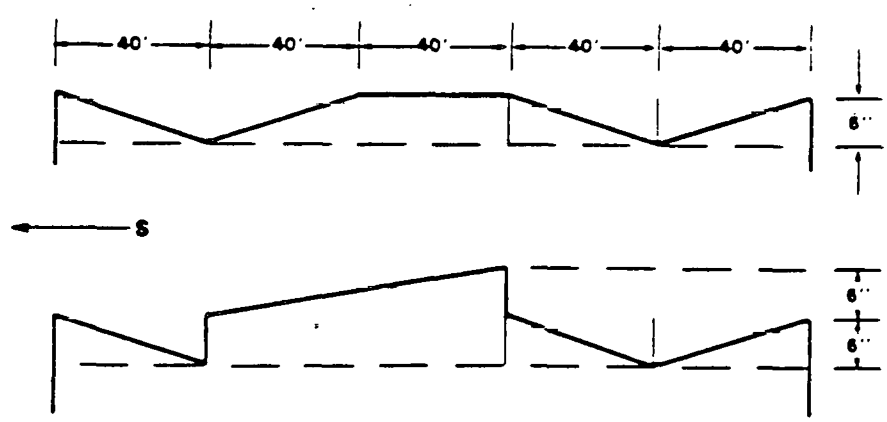


Figure 4-1. Roof Profiles (Vertical Scale Exaggerated)

required, it was found that the roof conformation was only approximate. This may be inherent in precast concrete structures of the OCSA type.

A design change was proposed by the general contractor. The supports were made up of two telescopic pipe sections, the lower section having a flange for bolting to the concrete and the upper section a plate to which the basic structural guides were attached. The lower sections were installed first, and the upper sections were installed to form a uniform plane. This required a significant amount of field welding but the net cost was somewhat less than determining the height of each column by survey, separate fabrications, etc.

4.1.2 Power Monitoring Instrumentation

The original instrumentation plan provided for separate sensors to measure each parameter for the DC and AC circuits. Ohio Semitronics produced a design that provided all required displays and outputs by integrating the instrument modules and sharing sensor and signal conditioning units. There was no significant reduction in cost for equipment, but installation and checkout were simplified.

4.2 DESIGN MODIFICATION

The design of the array supporting structure was based on the facility as-built drawings. During the design development task, a cursory check of these drawings had been made but no detailed survey was undertaken. During installation, it was found that a raised section of the roof was about 40 cm (16 inches) wider in the N-S direction than shown on the drawings.

The solution was relatively simple. The basic structure members had sufficient strength to tolerate being cantilevered 20 cm (8 inches) to permit placement of the foundations on the portion 20 cm (8 inches) north of their design location.

Hindsight clearly shows the desirability of analyzing the design for all critical interferences, and on-site verification of the correctness of the as-built drawings with regard to such interferences.

4.3 CHANGES DUE TO EXTERNAL FACTORS

Over the past few years, the scope of activities in the Kirkpatrick Center has grown several fold. While this expansion can be considered beneficial with regard to the public exposure of the photovoltaic system, it did, however, create certain problems. The internal coordination of diverse activities including allocation of space to new exhibits and communications of day-to-day decisions became both cumbersome and informal. As a consequence, during the interval between completion of the design and the award of the general construction contract, an air and space museum was installed on the second floor which included the space allocated earlier for the PV electrical equipment room. Further, two air conditioning units were installed on the roof to serve the museum; these interferred with the planned location of one of the source circuit structures.

It was necessary to assign a new space for the equipment room and to modify the structure location for one source circuit. Four drawings had to be revised and it was necessary to delay the closing period for general contractor bids.

This problem could have been avoided by ensuring certain early actions. First, a timely recognition should have been given to the degree of decentralization and informality of actions in space allocation and planning that were at the time in effect within OCSA. The availability of a SAI project member on-site at the center to represent the project in the day-to-day decision making would have been very beneficial. Second, all OCSA personnel involved in planning for the facility should have been more thoroughly and continually acquainted with the specific details of the PV system.

SECTION 5
IMPLEMENTATION EXPERIENCE

5.1 MODULE PERFORMANCE AND DELIVERY

The original module specification was for a 61 cm x 122 cm (2 ft x 4 ft) module with an average power output of 70 watts at 25^{o}C and AM1 insolation of 1,000 w/m^2. Solarex had developed a production capacity for 10.2 cm x 10.2 cm (4 in x 4 in) cells which required a larger module to suit the balance of the specifications. As a result, Solarex requested a change in the specification to permit use of the larger module.

An analysis of the cost impact indicated an increase in structure cost per module of about 11 percent. This was acceptable if the module output was 11 percent greater. While Solarex indicated confidence that 77.7 watts per module was attainable, they were reluctant to accept that specification until their production techniques were proven.

A satisfactory agreement was arrived at on the following basis:

- SAI's general construction contract would call for a basic structural and electrical package for 18 source circuits and for options for a 19th and a 20th source circuit. The 18 source circuits would meet system requirements if the average module output was equal to or greater than 77.7 watts. If the average output was less than 77.7 W, but equal to or greater than 73.7 W, 19 source circuits were required. If the average module output was less than 73.7 W, 20 source circuits were required.

- The module contract called for a total of 117,000 watts in 1512, 1596 or 1680 modules, with a price per module such that the total system cost (modules, structure and wiring) would be equal. The average power output was to be determined by the performance of the first 300 modules. This restriction was necessary to permit exercise of the options for the 19th and 20th branch circuit structures before the general contractor completed the initial steel fabrication.

The module delivery schedule was delayed due to early production problems. Polycrystalline cell modules with efficiencies of about 11 percent (based on total cell area) had been produced on a small scale during Phase I. However, the average efficiency of the early production modules was on the order of 7 percent.

To minimize an adverse impact on the installation schedule, the project monitor at DOE-Albuquerque consented to qualification testing of modules which were deficient in power output. These modules were to be qualified with respect to the mechanical and electrical tests except that the results of these qualification tests would apply to power output of the production modules on a relative basis only. The eventual acceptance of both the qualification test results as well as the modules for incorporation into the OCSA PV system was conditional on production deliveries meeting or exceeding the average minimum power output requirement of 70 watts at 1 Kilowatt per square meter of illumination and 25^{o}C, as stated on the previous page.

5.2 UTILITY COMPANY PARTICIPATION

The local electric utility, Oklahoma Gas & Electric Company (OG&E), was a participant in the project from the beginning of Phase I. At that time there had been no other OG&E grid-connected customer owned generators and there were neither technical standards for the interface nor applicable regulations for buy-back of excess energy.

OG&E undertook the design of the interface between the PV system and the utility service to the OCSA facility. Their primary concern was for the safety of personnel working on a de-energized utility system. The initial design incorporated a monitor to measure the ratio of the third harmonic to the 60 Hz fundamental, and a dial-in feature to permit remote query of this interface sensor. Since the third harmonic content of the PCS output would be much greater than that normally present on the utility service line, it was believed that the monitor would permit positive determination of the status of the PV-utility switch.

Subsequent analysis indicated that the initial design was more elaborate than necessary. A preliminary failure mode and effects analysis of the PCS circuit showed that there was virtually no combination of failure that would result in the output of AC power into a de-energized utility line. In addition, the step-up transformer between the PCS and the utility service prevented the introduction of a DC component into the utility.

In the interval between the start of Phase I and the completion of Phase II, OG&E had numerous requests for connection of privately-owned power sources (primarily wind turbines). To meet this demand, they established a standard interface for all such devices. The interface requirement was very simple -- each system was to be connected to the utility tie-point by a switch that could be locked in the open position; such a switch was to be accessible to OG&E personnel at all times; and only OG&E was to have a key to the lock. This interface design was used for the OCSA system.

5.3 MODULE MATCHING

The system construction schedule was based on delivery of all modules prior to the completion of the array structure to make efficient use of site manpower. The installation of structure was nearing completion yet at that point in time only about 35 percent of the modules were delivered to the site. The delay in deliveries threatened to interrupt work at the site. Waiting for delivery of the remaining modules would have involved not only the removal from and subsequent deployment of the construction crew to the site but also meeting a demand by the construction contractor for substantial escalation in cost since the remainder of the modules were expected to be available in batches of 100 to 200 modules at a time covering a total period of six months.

To minimize the adverse impact of late deliveries of modules it was decided to assign modules to source circuits using the statistical distribution of I_{SC}, I_{MP}, and V_{MP} for the first 600 modules. In doing so, it was assumed that subsequent deliveries would have the same distribution of module electrical parameters. The modules supplied by Solarex were individually measured to determine their performance characteristics. These measurments were necessary for two reasons. First, only modules with output power at least 85 percent of their design rating were acceptable under the contract. Second, performance characteristics varied significantly. Modules with similar performance characteristics were placed in each string to ensure the most optimum performance. Groups of 84 modules were assigned to source circuits to provide nearly equal currents for modules within a source circuit and nearly equal voltage for each source circuit.

The matching was complicated by the characteristics of the polycrystalline modules. Figure 5-1 illustrates the I-V curves for two typical modules. Both have approximately the same peak power currents and voltages, but markedly different short-circuit currents. Had the modules been matched by I_{SC}, for example, there would be mismatch under conditions approaching the maximum power point. On the other hand, if matching was conducted by I_{MP}, the modules will be mismatched whenever the operating voltage was less than V_{MP} (the PCS was equipped for both the peak power and constant voltage operations). Therefore, it was necessary to match modules by using both I_{MP} and I_{SC}. The primary matching parameter was I_{MP} and the secondary parameter was I_{SC}-I_{MP} (in effect the slope of the I-V curve to the left of the maximum power point). A matrix of I_{MP} versus (I_{SC} - I_{MP}) was developed to facilitate grouping of modules. This led to a relatively fine degree of stratification of modules and at times, the secondary variable was given little weight in the module assignment process. In addition, as deliveries progressed, the module characteristics changed. Figure 5-2 shows a decrease in the average I_{MP} that occurred as the different shipments were received from Solarex. There was also a corresponding increase in the average V_{MP} since the average power remained the same. In the first shipment the voltage at max power averaged 5.1 V, and by the end of the last shipment it was averaging 5.5 to 5.6 V.

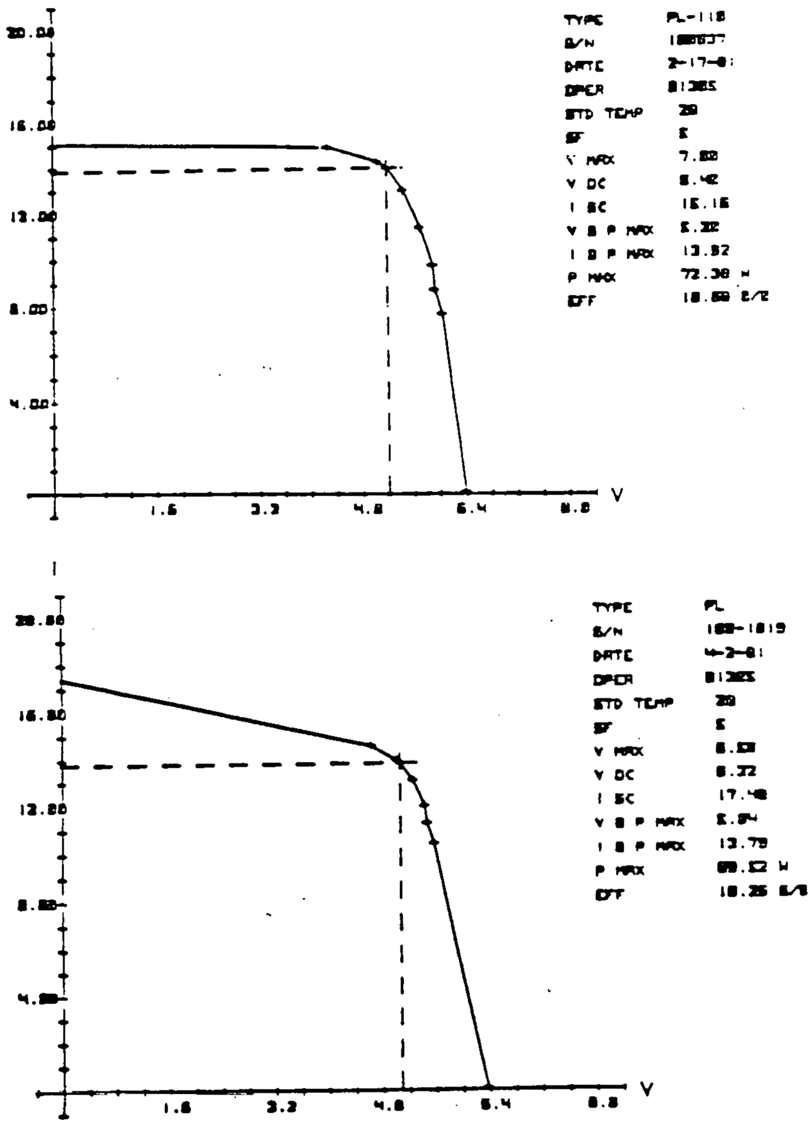


Figure 5-1. I-V Characteristics for Two Typical Solarex Poly-Si Solar Cell Modules

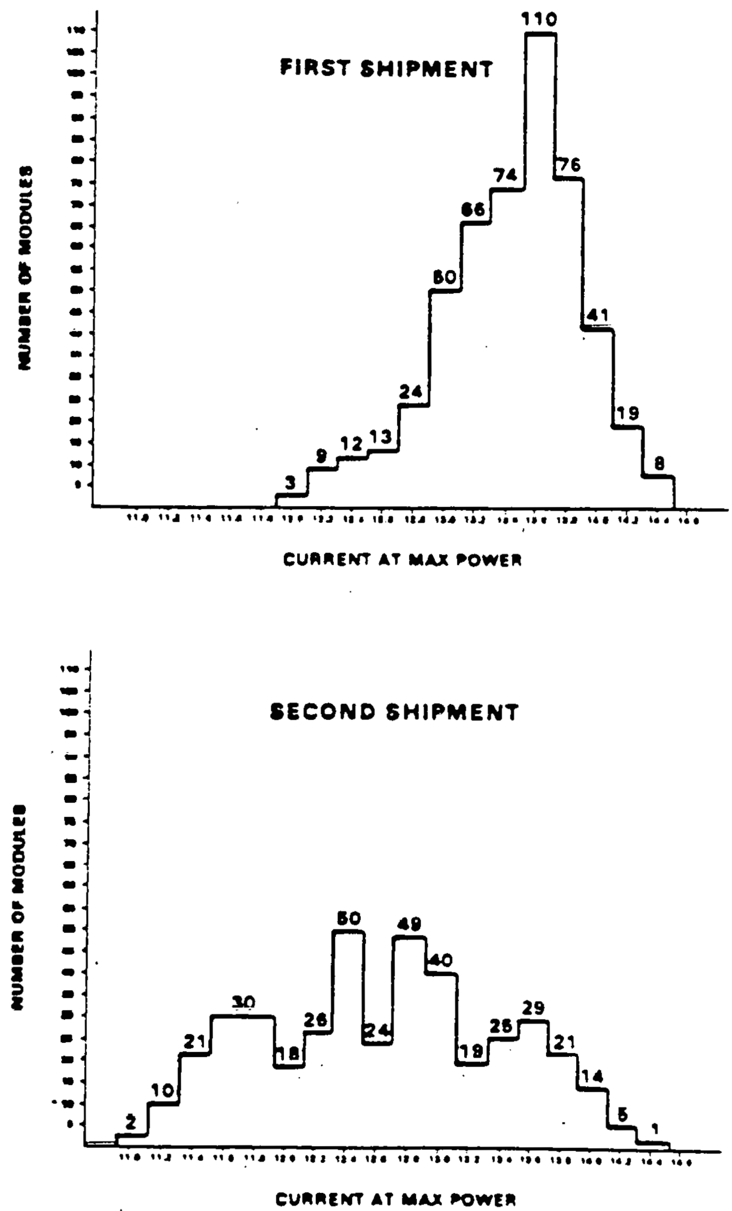


Figure 5-2. Histograms Illustrating the Decrease in Maximum Current of the Solarex Poly-Si Modules as They Were Manufactured and Shipped.

Hindsight proved it to be a questionable decision to match modules on the basis of the distribution of electrical parameters for the first 600 modules only. Although such an approach was satisfactory for an incremental assignment, the modules delivered later had significantly different characteristics which made it necessary to re-assign about 80 modules to achieve acceptable matching. The change in characteristics was probably due to maturity of the bulk material and cell manufacturing processes. However, until further experience is gained with polycrystalline module production, the assignment of modules to source circuits in advance of receipt of measured data for all modules is not recommended.

Another adverse of this substantial delay in beginning module production and deliveries to SAI was to limit the size of the PV system to an array field of 18 strings. The SAI's construction contract called for a basic structural and electrical package for 18 source circuits with options to be exercised for a 19th and 20th source circuit should module output not come up to expectation, i.e., 77.7 watts maximum at 25^{o}C. Work on the array support structure contract was on schedule. Shortly after all roof penetrations for 18 source circuit array field had been completed, it became clear that the initial production and deliveries of modules would be substantial delayed. The initial production runs were to be the indicators of the expected power output from the modules. The lack of availability of this data and the necessity to complete all roofing work prior to the onset of the winter season to mitigate any damage from leaks in the roof to the highly valuable Art and Science exhibits in the center mandated that the system size be limited to an array field of 18 source circuits.

5.4 RELATIONS WITH CONTRACTORS

No significant contractual problems were encountered in Phase II. A single general contractor was responsible for all steel fabrication and erection, roofing, electrical work, carpentry and installation of SAI provided items (modules, reflectors, electrical equipment, meteorological station and instrumentation).

The roofing and steel fabrication subcontractors had union agreements and the electrical subcontractor was non-union. The modules were installed by the steel erector and the module to module interconnections were made by the electricians. There were no jurisdictional disputes.

On-site inspections were provided by engineers from the Benham Group, an Architectural and Engineering firm with offices in Oklahoma City. The Benham Group was under contract to SAI. The terms and conditions of the general construction contract specified the role of the Benham Group to be that of an owner's representative on site, but he was not authorized to sign off design or installation changes without express approval of the SAI project engineer.

Change requests were evaluated for technical suitability and cost impact by representatives of the Benham Group and their recommendations were forwarded to SAI for analysis, review and approval. There were very few change orders for a project of this size.

5.5 ROOFING PROBLEMS

The OCSA facility has an essentially flat roof. The precast concrete roof members are covered with layers of rigid insulation, a built-up felt and tar membrane, a layer of styrofoam and coarse pebbles.

Installation of the PV system required in excess of 300 penetrations of the membrane to the precast concrete members and two penetrations through the concrete (for conduit and a hose bib). The original roof was only two years old.

The warranty on the original roof would be effectively voided by the penetrations since there would be no objective means of proving that the leak was attributable to the original installation. Similarly, the PV system general contractor would not accept responsibility for leaks since they could be the fault of the original roofing. The only acceptable solution was to replace the entire roof membrane. The contractual terms provided a warranty to SAI (the "owner") which would be conveyed to the OCSA board of trustees upon completion of Phase III.

5.6 HAIL EXPERIENCE

Hailstorms occur in the Oklahoma City area quite frequently. The size distribution of hailstones can vary substantially from one event to the next. The majority of hailstones in this region are below 4 cm in diameter, although hailstones of 5 cm (2 inch) in diameter and larger have been reported. The recorded data in one case even indicated a hailstone of about 10 cm (4 inch) in diameter, reported to be sighted by a casual observer in Edmonton, Oklahoma.

During qualification testing several modules were subjected to hailstone impact tests. The ice balls, simulating hailstones, used for impact testing varied in diameter from 2.5 cm (1 in.) to 7.5 cm (3 in.).

Results of JPL hailstone impact tests showed a negligible probability of breakage of 5mm (3/16 inches) tempered glass superstrates by about 3.8 cm (1.5 in.) diameter hailstones. A test conducted with a 7.5 cm (3 inch) diameter ice ball was clearly damaging, while tests with 5 cm (2 inch) diameter ice balls indicated some potential for damage from impacts near the edges of the unframed module. The probability of damage from 5 cm (2 inch) diameter hailstones can be of the order of 0.3 from impacts near the edge of the module, and decreases very rapidly with the distance of the impact point from the edge.

The Kirkpatrick Center is located on the border between a severe and a moderate hail environment. Extensive analysis of all published data and some excellent site specific raw data obtained from the National Severe Storms Center in Norman, Oklahoma indicated that the risk of damage to the modules was acceptable.

On 9 June 1981, a severe hailstorm impacted the Oklahoma City area. Stones in excess of 7.6 cm (3 in.) diameter fell on areas about 80 km (50 miles) SW of the city. The system was partially installed at the time. A workman who went to the roof immediately after the storm passed reported large, approximately 3.6 cm (1 1/2 in.) diameter stones, about one for each 0.37 m^2 (4 square foot) of roof area. No modules were damaged. Several reflectors which had been set in place but not bolted down, were blown off the structure by the 40 knot (46 mph) winds and were broken. However, no installed reflectors were damaged.

5.7 FAILURE EXPERIENCES

Three failures occured during the initial operation of the system. Each is described below.

5.7.1 PCS Input Filter Capacitor

During the first two weeks of operation, a 450 VAC 3,100 fd capacitor (one of two in the PCS input filter circuit) failed. The failure was presumably caused by voltage stress during the early hours of operation before final adjustment of the peak power tracking circuit. (Voltage excursions of up to 500 V were observed at initial turn-on.).

5.7.2 PCS Input Filter Inductor

During the fourth week of operation, the 6 mH inductor in the PCS filter circuit developed an internal short. The inductor is wound with a wide strip of sheet copper rather than with wire. It is probable that the fault was due to a manufacturing defect or mishandling during assembly of the PCS.

5.7.3 Short Circuits in the Wiring of Source Circuit 16

A short circuit occurred between the positive and negative wires of source circuit 16 at the point where the wires entered the large SPC box on the roof. The wires burned through and melted a length of conduit. The failure was attributed to inadequate conduit support combined with the omission of antichafing bushings at the conduit outlet. Subsequent to this failure, antichafing bushings were installed at all conduit outlets.

5.8 SYSTEM COST SUMMARY

A summary of system costs incurred during Phase I - System Design and Analysis and Phase II - System Fabrication, Construction, Integration and Acceptance Testing is shown in Table 5-1.

Table 5-1

System Cost Breakdown, Phases I & II Combined

Cost Item	Dollars in (1000)	Percent of Total Cost
System Design & Engineering, Including Project Management	405	13.6
Site Preparation (Primarily Replacement of Roof Membrane)	217	7.3
Collector & Mirrors, Including Installation	1696	57.0
Array Foundation, Supporting Structures, Penetrations, etc.	374	12.6
PCS & Control Subsystem	96	3.2
Electrical Wiring, Switchgear, etc.	140	4.7
Instrumentation, Display and Miscellaneous	49	1.6
Total	2977	100

SECTION 6
PERFORMANCE SUMMARY

6.1 INITIAL OPERATION

Installation and system checkout were completed on 11 February 1982. The Phase II period of operation lasted 64 days, until 17 April 1982. During Phase II, the PV system was up for 17 days, essentially all of it in February 1982, and down for 47 days. All downtime was due to failures in the inverter. The failure of the capacitors caused the system to be down for 9 days while replacements were being shipped. The inductor failure on March 10 caused the system to be down for the remainder of Phase II (38 days) while the inductor was being re-manufactured.

6.2 ARRAY PERFORMANCE

Several anomalies were noted during the initial period of operation. The PCS showed an efficiency in excess of 100 percent and the currents from the two subarrays differed by as much as 21 percent. The power instrumentation was recalibrated. The total energy generated during Phase II was 5663 KWhr (an average of 354 KWhr per day) for the 16 days the system was operational. Since all system operating hours were in the winter months when the sun's elevation was too low to effect any reflector enhancement of the array output, the energy generated by the system during this period was essentially without reflector augmentation.

An extrapolation of the measured power output to $25^{o}C$ and 1,000 W/M^{2} under conditions of no reflector augmentation provides a value of 89 kW. This estimate is probably on the high side since some reflector augmentation of diffuse insolation can be expected in addition to diffuse radiation potentially incident on the modules due to scattering from snow on the ground during this period of operation. The measured power output of the PV array was significantly below the design point output of 101.5 kW. The PV array design point output estimates with and without reflector augmentation at a cell temperature of 25° C and AMI insolation of 1,000 w/m^2 incident on the array are shown in Table 6-1. A systematic analysis to isolate the source of the shortfall was hampered by the three failures described earlier. Nonetheless, it appeared virtually clear that the PV modules had a much lower output than the manufacturer's test data showed.

Table 6-1. Estimated PV Array Design Point Output at 25°C and 1,000 W/m^2 Insolation

• 1512 installed modules at 70 W average per module		105,840 W
• Mismatch losses @ 2 percent*		2,117 W
	Balance 103,723	
• Conductor and diode losses*		2,200 W
	DC power (no augmentation)	101,523 W
• Reflector augmentation effects (peak)**		
800 W/m^2 direct insolation (35 percent)		28,427 W
200 W/m^2 diffuse (11 percent)		2,234 W
	Total	132,184 W

*All output loss estimates are maximum values based on design parameters.
**The reflector augmentation estimates are based on a mirror reflectivity of 0.75.

The measured power output of the PV array falls short of the design value by about 12 percent. Potential sources of a false indication could theoretically include:

- Module fouling
- Excessive conductor and diode losses
- Losses to ground
- Excessive ripple on the DC bus
- Instrument calibration errors
- Temperature sensor errors

The potential contribution from each one of these factors to the shortfall in the system output is briefly discussed next.

6.2.1 Module Fouling

Atmospheric pollutants in the Oklahoma City area appear to be benign. The modules and reflectors collect dust during dry periods, and the dust level was somewhat aggrevated by construction work in progress adjacent to the site. However, after a rain, the reflectors and most of the module surfaces appeared clean. A "white-glove" test did not reveal residual dust on the apparently clean surfaces.

On many of the modules, a very thin deposit of clear RTV on portions of the superstrate had become apparent. This was not visible when the modules were new, but the deposit could accumulate dust and dirt which persist after washing with water and commonly available cleaning solvents. The dimpled surface of the glass precludes simple mechanical removal of the deposit by scraping. It is estimated that about 50 percent of the modules could have such deposits with a total area equivalent to the area of one cell.

While no accurate computation of the resultant loss is practical, an extreme value for blockage could not exceed 30 percent of the light incident on the fouled areas, and with about 100 cm^2 distributed over each of one-half the modules, the total loss would not be expected to exceed 2 percent of the output.

Efforts to remove the deposits by mechanical and chemical means will continue. Care must be exercised in attempting chemical removal since the bonded edge gaskets are of essentially the same material. The presence of the deposits is attributed to lack of care exercised during the encapsulation process.

6.2.2 Conductor and Diode Losses and Losses to Ground

Conductor resistance from the source circuits to the string power collection boxes (SPC), between the SPC boxes and the equipment room, and from the equipment room terminations to the PCS were measured. They were within the specified tolerances for the size and type of conductors used. Conductor to ground measurements indicated no cable faults. The total losses attributable to the conductors, diodes and circuit breakers on the DC circuits were estimated at less than 2.5 kW at 100 kW input to the PCS.

Current flows through the ground points of the system were not yet measured.

6.2.3 DC Bus Ripple

Ripple on the DC bus was observed with an oscilloscope. The maximum peak-to-peak voltage of any significant low frequency ripple was 10 V. Losses attributable to ripple are obviously negligible.

6.2.4 Instrument Calibration

The instrumentation for measurement of AC and DC current and voltage was checked and recalibrated as required. The initial checks indicated too high an output for the PCS output currents. The main DC bus voltage sensor appeared to have an intermittent error of about 10 percent, but this has not been observed since recalibration. All power instruments on the DC circuits and the PCS power output circuit have been calibrated using instruments with tolerances of 0.05 to 1.0 percent of reading. It was estimated that the cumulative worst case effect of calibration errors would be less than 1.5 percent.

6.2.5 Temperature Sensor Errors

The module temperature sensors are "UNI-CURVE" thermistors. The 42 sensors in the array read within about one-half degree centigrade of each other during steady-state conditions and there were no indications of faults. The sensors are insulated from the cells by about 2 to 3 mm (0.08 to 0.12 in) of SYLGARD-184. The thermal conductivity of the encapsulant is .00035 $cal/cm^2/^{o}C/sec/cm$. This should result in a small error since the heat dissipation of the back surface of the module is to relatively calm air, and the thermal conductivity of the glass superstrate is 3 times that of the encapsulant.

An identical thermistor was coupled to the superstrate directly over a cell that had one such thermistor on its rear surface. Comparison of these readings indicated that the temperature sensors provided outputs within $2^{o}C$. Further experiments will be conducted to develop correction curves for the thermistor to take the insulating effect of the encapsulant into account.

6.3 PCS PERFORMANCE

The AC output of the six-pole inverter is not a clean signal. The SCR switching transients caused apparent interference to certain electrical loads in the OCSA complex. Characterization of the noise was not completed during Phase II. It will be the subject of a special topic report during Phase III.

The planetarium audio system was the most seriously affected load. A preliminary investigation of the existing facility wiring revealed the use of practices that could degrade the power quality in the presence of conducted and radiated interferences. Cable shields had been grounded at both ends, frequently to ground points of different impedance. In some cases, the lighting circuits were used as grounds. The application of good shielding, bonding and grounding practices reduced the interference by about 85 percent. Further efforts were continuing to eliminate the residual.

The PCS efficiency was essentially as predicted, but data at the design peak power are lacking because of the low output of the array.

6.4 CONCLUSIONS

At the near completion of Phase II the only serious problem the system had was the shortfall in its electrical output. The source of the poor array performance appears to be the shortfall in module outputs. Five modules selected randomly from those at OCSA were shipped to the Jet Proulsion Laboratory (JPL) for power output measurements. The JPL tests showed an average power output 12 percent lower than that indicated by the manufacturers test data supplied with the module deliveries. PV array and module performance evaluations would continue during Phase III to delinate the cause of and to rectify the problem of shortfall in system output.

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